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PAPER

Usability and Performance Evaluation of a Mobile Application for Learning PID Controllers: A Case Study with Engineering Students

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ABSTRACT

In the academic field, especially in contexts with limited technological resources, it is essential to provide tools that facilitate both the theoretical understanding and the practical application of PID controllers. This study evaluates the usability and performance of TempRes ControlSys Simulator, a mobile application developed to enhance practical learning of automatic control. Through a non-experimental case study, the User Experience Questionnaire (UEQ) was applied to assess the perception of usability, as well as BlazeMeter to analyze performance. The results reflect a moderate usability of the application, with 60% of the students highlighting its clarity, efficiency, and precision. In terms of performance, the results show that the mobile application responded optimally to the expected demand within the case study. It is concluded that the mobile application represents a viable and accessible alternative in educational environments with technological limitations, favoring inclusion by facilitating access to practical simulation tools. Future research should integrate external sensors for real-time signal acquisition, allowing its application in real scenarios such as the handling of robotic arms or the automatic orientation of solar panels, reinforcing the connection between simulation and experimentation in mechanical and electrical engineering students.

KEYWORDS

mobile application, usability, performance, automatic control, PID controllers

1 INTRODUCTION

Technological advancement has driven significant transformations in higher education, where mobile devices have gone from being complementary tools to fundamental resources for digital learning, promoting accessibility to academic content and flexibility in teaching [1]. This trend has been particularly evident in technical disciplines and engineering, where the incorporation of mobile applications has facilitated the

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development of specific competencies and has generated new teaching methodologies that promote learning autonomy [2]. In addition, recent research has indicated that the integration of digital tools in the university classroom not only optimizes accessibility to information but also increases student motivation and commitment, favoring interaction and collaborative construction of knowledge [3]. In this sense, the use of mobile applications allows the design of more dynamic and interactive learning experiences, which contributes to the retention of concepts and a better understanding of academic content [4]. Studies have shown that mobile devices also promote self-regulation of learning, a key aspect in the training of professionals in highly demanding educational environments, such as engineering [5]. Based on this evidence, it is possible to affirm that the incorporation of mobile applications in higher education represents a significant advance in the digital transformation of teaching, providing new opportunities for pedagogical innovation and improving students' academic performance [6].

In this context, usability emerges as a key factor in the design and evaluation of educational mobile applications, as it directly influences the user experience and the effectiveness of learning. According to the ISO 9241-11 standard, usability is defined as the degree to which a product can be used by specific users to achieve specific objectives with effectiveness, efficiency, and satisfaction in a given context [7]. Evaluating the usability of an application involves analyzing various attributes, such as the clarity of the interface, ease of navigation, and user satisfaction, in order to optimize its design and functionality. Various studies have shown that measuring usability in learning environments requires standardized instruments that allow the user experience to be quantified objectively [8]. Among the most widely used methods, the User Experience Questionnaire (UEQ) has gained relevance by providing a comprehensive approach to assessing user perception in terms of attractiveness, clarity, efficiency, accuracy, stimulation, and novelty, making it a suitable tool for mobile applications [9], [10]. Its application in studies on mobile learning platforms has allowed us to identify strengths and areas for improvement in terms of accessibility and ease of use or effectiveness in teaching [11]. The importance of evaluating usability in mobile applications allows us to guarantee their acceptance and optimize their design based on the user experience [12].

In addition to usability, the performance of mobile applications in educational environments is a determining factor to ensure their functionality and accessibility, especially when implemented in high-demand contexts. Performance tests, such as load and scalability tests, allow evaluating an application's ability to support multiple users simultaneously without compromising its stability or response times [13]. Tools such as BlazeMeter have proven effective in identifying bottlenecks and optimizing the performance of distributed systems, which is essential in mobile applications [14]. It has become essential to subject these applications to tests that simulate real usage conditions by evaluating metrics such as latency, resource consumption, and system resilience to variations in demand [15]. The relevance of incorporating auto-scaling strategies in mobile applications is evident, allowing cloud services to dynamically adjust available resources based on user load, ensuring a fluid and uninterrupted experience [16]. In this context, the evaluation of mobile application performance is essential to ensure its operational stability and scalability, allowing its optimal functioning and avoiding failures that may affect the user experience in high-demand digital environments [17].

This study arises as a continuation of previous research on the development and implementation of a mobile application for learning tuning and self-tuning of PID (Proportional-Integrator-Derivative) controllers in engineering students [18]. In particular, this study aims to evaluate the usability and performance of the TempRes ControlSys Simulator mobile application, developed with the purpose of improving accessibility and effectiveness in the teaching-learning process of the automatic control subject for mechanical and electrical engineering students. The study was carried out under a non-experimental cross-sectional design, since variables were not manipulated, but rather the perception of students was observed and measured at a specific time. In addition, a quantitative approach was adopted for the evaluation of usability using the UEQ instrument and performance through load and stability tests in BlazeMeter. Therefore, the study answers two research questions:

- RQ1: What is the perception of the usability of the mobile application for learning PID controllers by mechanical and electrical engineering students?
- RQ2: What is the performance of the mobile application for learning PID controllers in terms of load and scalability when used by mechanical and electrical engineering students?

2 THEORETICAL FRAMEWORK

Automatic control is a fundamental concept in control engineering that is responsible for regulating a physical variable within a specific range in an automated industrial environment. To achieve this, it makes use of principles of control theory, analysis methods, and practical applications in dynamic systems [19]. Its study allows us to understand how systems respond to different inputs and how to design efficient control strategies to optimize their performance. Under the concepts necessary for the development of the TempRes ControlSys Simulator mobile application, the topics of temporal response of control systems and tuning of PID controllers were addressed in this theoretical framework.

2.1 Time response of control systems

El Time response analysis is essential to understand the dynamic behavior of a control system. In general terms, two types of responses are studied: transient responses and steady-state responses [20]. The transient response describes how the system responds to an input before reaching its steady state or final state. It is characterized by parameters such as rise time (T_r), delay time (T_d), settling time (T_s) and overshoot (M_p) and steady-state error. The steady-state response evaluates the behavior of the system after a long time, allowing them to determine the control accuracy [21]. Mathematically, the response of a second-order system to a step input is described by equation 1 [20].

$$G_{(s)} = \frac{\omega_n^2}{S^2 + 2 * \rho * \omega_n + \omega_n^2} \tag{1}$$

Where ω_n is the natural frequency of oscillation, and ρ is the damping factor. The behavior of the temporal response depends on the value of the damping factor, i.e., the system will be oscillating if the damping factor is equal to 0, while the system will be underdamped if the damping factor is between 0 and 1; however, if the damping factor is 1, the system will be critically damped, and if the value of the damping factor is greater than 1, the system is considered overdamped [22]. Figure 1 shows the temporal response of an underdamped control system in reaction to a unit step input signal [23]. The control system will be considered stable if the temporal response reaches a value with a steady-state error equal to zero and when the final value of the response coincides with the set-point value. However, when the control system does not achieve stability, one of the possible strategies is to use PID controllers.

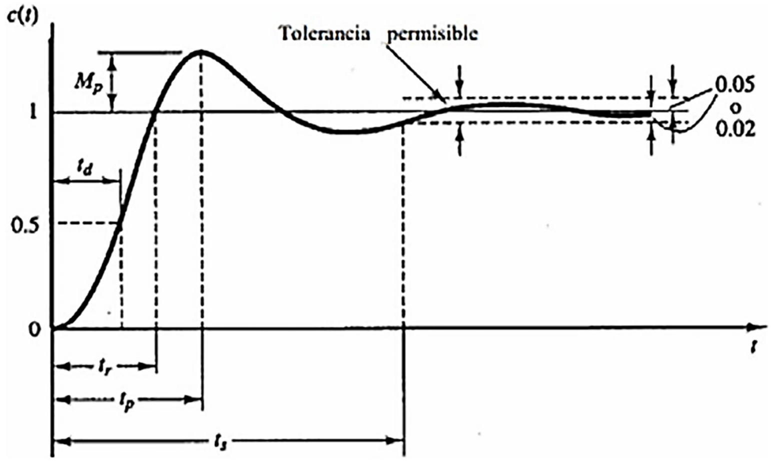

Fig. 1. Time response of the controlled variable

The settling time for second-order systems is determined from the moment in which the temporal response of the controlled variable remains within ±2% of the final value and is calculated through equation 2 [20].

$$T_s = \frac{4}{\rho * \omega_n} \quad (2)$$

2.2 PID Controller Tuning

A PID controller has been a fundamental tool in the field of automated control for more than one hundred years, consolidating itself as the predominant option in the industry thanks to its simple design and efficient operation; it is estimated that ninety percent of the control systems incorporate it, since it allows a precise regulation of processes in a wide variety of industrial applications [24]. Its widespread use is due to its capacity to improve the stability of the system and minimize errors in the response of the controlled variable [25]. In addition, the scheme of a PID controller can be implemented under a parallel structure of three components: the proportional, the integrative, and the derivative [26]. However, PID controllers over time have made various modifications in their design to improve their stability and adaptability in complex dynamic systems [27]. Figure 2 shows the scheme of a closed-loop control system with a PID controller [28].

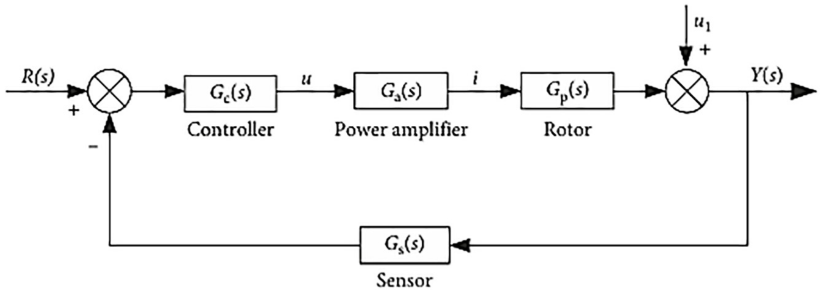

Fig. 2. Diagram of a closed-loop control system with a PID controller

The expression that relates the error signal with the control signal ($\mu_{(t)}$) in the architecture of the automatic control system is the one shown in equation 3 [24]. In addition, by applying the Laplace transform, it is expressed as shown in equation 4 [27].

$$\mu_{(t)} = K_p * e_{(t)} + K_i * \int e_{(t)} dt + K_d * \frac{de_{(t)}}{dt} \tag{3}$$

$$U_{(s)} = K_p * E_{(s)} + \frac{K_i}{s} * E_{(s)} + K_d * s * E_{(s)} \tag{4}$$

Where K_p, K_i, and K_d are the proportional, integrative, and derivative gains of the PID controller, and the way of determining them will depend on the control system being analyzed and the desired performance. One way to determine these constants is through controller tuning, for which, within the various methods that exist, are those linked to the Ziegler-Nichols. There are two methods, the first called the "Reaction Curve" method, which is used when the transfer function of the plant or process is unknown, so that when a unit step type input signal is applied to it, the output must be a sigmoidal type signal, in which the controller gains are determined through the constants T_d (delay time), T (time constant) and K (static gain), as shown in Figure 3 [29]. It is based on identifying the inflection point of a sigmoidal curve, and from this point, a tangent line is drawn to the curve, allowing the determine of the intersection with the time axis and, in this way, establishing the values of the constants T_d and T that allow the definition, on the other hand, of the transfer function of the plant or process [30].

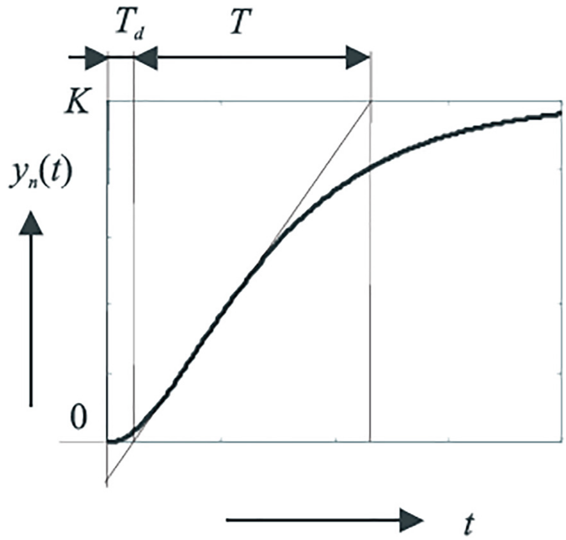

Fig. 3. System reaction curve in the Ziegler & Nichols method

While the other method is called "Sustained Oscillations," this method is used to determine the controller constants for scenarios when the order of the control system transfer function is greater than three. It consists of identifying the gain and the period in which the plant or process is within a state of permanent oscillations. In this context, the value of K_c (Critical gain) and P_c (Critical period) are determined, and thus the controller gains. [31]. Figure 4 shows the scenario of sustained oscillations of the plant or process under analysis.

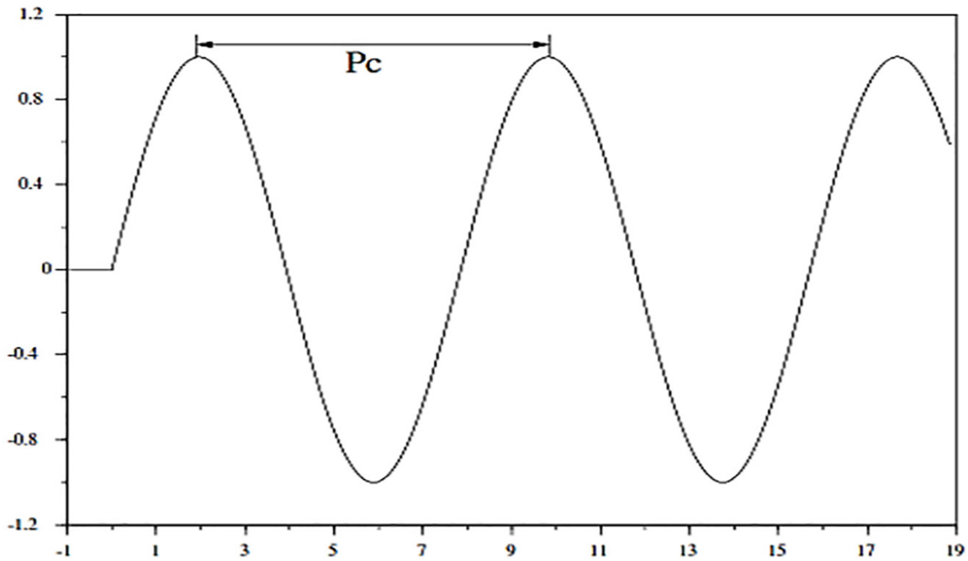

Fig. 4. Scenario of sustained oscillations of the plant or process under analysis

3 MATERIALS AND METHOD

3.1 Materials

The TempRes ControlSys Simulator mobile application was designed as an educational tool to facilitate the understanding and simulation of control systems, focusing on the temporal response of dynamic systems and the tuning and self-tuning of PID controllers. For its development and implementation, various technological tools were used that allowed the integration of interactive functions, cloud processing, and user authentication, guaranteeing a safe and accessible environment for mechanical and electrical engineering students.

The development of the application was structured in three levels: frontend, backend, and cloud services, allowing efficient communication between the system components. The frontend was implemented in Android Studio using Jetpack Compose, which allowed the creation of the interfaces. The backend was developed in Python within Visual Studio Code, using specialized automatic control libraries for the calculation and representation of the temporal response and the tuning of PID controllers. In addition, to host and manage the backend endpoints, Heroku was used with 1 Dyno, providing a public IP address for communication with the mobile application. For communication between the frontend and backend, Retrofit was used, an Android library that optimizes HTTP communication with cloud services. Finally, to ensure security and access control to the application, an authentication system based on Firebase Authentication was implemented. This system allows users to register and access the application by verifying institutional emails and managing their passwords.

Figure 5 shows the user interfaces; Figure 5a shows the authentication interface, and Figure 5b shows the presentation interface, which basically highlights that the mobile application has two main functions: "Temporal response of the Control System" and "PID controller tuning and auto-tuning." Figure 5c shows the deployment of the modules of the first main function, "Temporal response of the Control System," while Figure 5d shows the deployment of the modules of the second main function, "PID controller tuning and auto-tuning."

In order to demonstrate the functionality of one of the modules of the TempRes ControlSys Simulator mobile application, the module "Determine PID controller constants using the sustained oscillation method" was chosen, corresponding to the second main function. Figure 6 shows the interfaces for data entry and the time response curves of the controlled variable using PID controller tuning using the Ziegler and Nichols method. Figure 6a shows the data entry of the transfer function, as well as the simulation time (12 seconds) and the type of controller, which in this case was chosen as the PID controller. The result is the critical gain Kcr = 29.97 and the value of the critical period Pcr = 2.81. Figure 6b shows the PID controller gains generated by the simulator, in which Kp = 17.98, Ki = 12.80, and Kd = 6.32. In addition, it is possible to enter new values for the controller gains to improve the response of the controlled variable. Figure 6c shows the new response of the control system generated by considering the new gains entered manually; in this case, manual_Kp = 29, manual_Ki = 12.80, and manual_Kd = 6.32. Finally, Figure 6d shows the performance of the controller with manual tuning and tuning by the sustained oscillation method.

Fig. 5. Mobile application interface: (a) Authentication, (b) Presentation, (c) Deployment of modules–main function 1, (d) Deployment of modules–main function 2

Note that the bottom part shows the open-loop time response curves, the sustained oscillation behavior, and the new closed-loop response when PID controller tuning is applied to the control system.

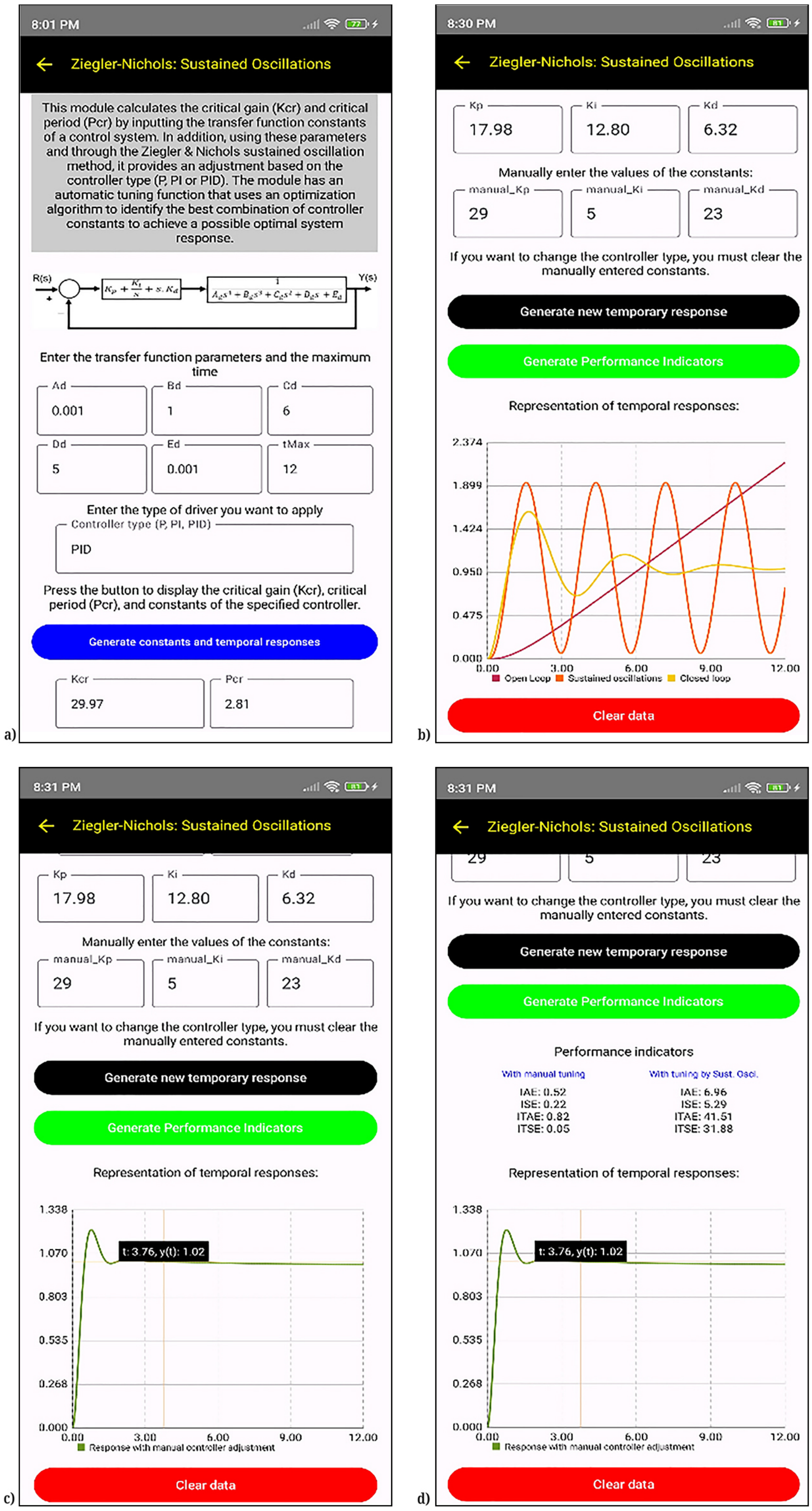

Fig. 6. (a) Data entry interface of the transfer function, (b) PID controller gains and graphs generated by the simulator, (c) new time response generated by manually entering the PID controller gains, (d) PID controller performance with manual tuning and tuning by the sustained oscillations method

3.2 Method

The study is framed as a case study since it examines in depth the use of the mobile application TempRes ControlSys Simulator in a specific group of Mechanical and Electrical Engineering students. Its approach is quantitative, since it focuses on the objective measurement of usability and performance indicators of the mobile application. Its scope is descriptive, since the purpose of the study is to analyze the factors that influence the usability and performance of the application, identifying opportunities for improvement. The study design is non-experimental and transversal, since no modifications were introduced in the conditions of use of the mobile application, and data collection was carried out at a single point in time. Although the mobile application was used as a support tool in the teaching-learning process, the study was not aimed at evaluating its impact on academic performance but at characterizing the user experience and the stability of the system under real-life conditions. The study population consisted of 30 students from the eighth cycle of the automatic process control course. Following the interaction, the UEQ was applied, allowing the collection of data on the perception of usability in key dimensions such as attractiveness, clarity, efficiency, and feasibility of use, with 7 levels of evaluation. It should be noted that when evaluating the reliability of the data collected with UEQ, a Cronbach's Alpha value equal to 0.969 was obtained. All data processing was performed using SPSS software, working with percentiles to recode the usability levels to only 3, these being low, medium, and high. On the other hand, for the purposes of measuring the performance of the mobile application, the load and scalability indicators were evaluated using BlazeMeter, with the aim of analyzing the stability of the system under different levels of demand. Simulations were carried out with 10, 20, 30, 40, and 50 concurrent users, measuring key metrics such as throughput, latency, and error rate, in order to determine the threshold from which the system's performance began to degrade.

4 RESULTS AND DISCUSSION

4.1 Usability perception results

The results obtained from the application of the UEQ instrument reflect a most favorable perception of the mobile application, with a predominance of responses at medium and high levels in all dimensions evaluated. The dimensions "Clarity" and "Efficiency" were highly valued by students, with 63.34% of the responses being at medium or high levels, which indicates that the majority considers that the application is understandable and allows tasks to be carried out effectively. Likewise, the "Precision" dimension obtained 53.33% of responses at medium and high levels, showing that more than half of the users trust the functionality of the system. Other dimensions, such as "Novelty" and "Stimulation," reflect that the application manages to capture the attention of students, and the perception of the "Attractiveness" dimension presented 63.33% considering the medium and high levels, representing that the interface is well received. These results indicate that, in general terms, students consider the application to be a useful and well-structured tool for learning the temporal response of control systems and tuning and auto-tuning of PID controllers, offering a user experience that facilitates understanding and interaction. Figure 7 shows the result of the students' perception of the mobile application, obtained from the use of the UEQ instrument, which measures user perception in six dimensions.

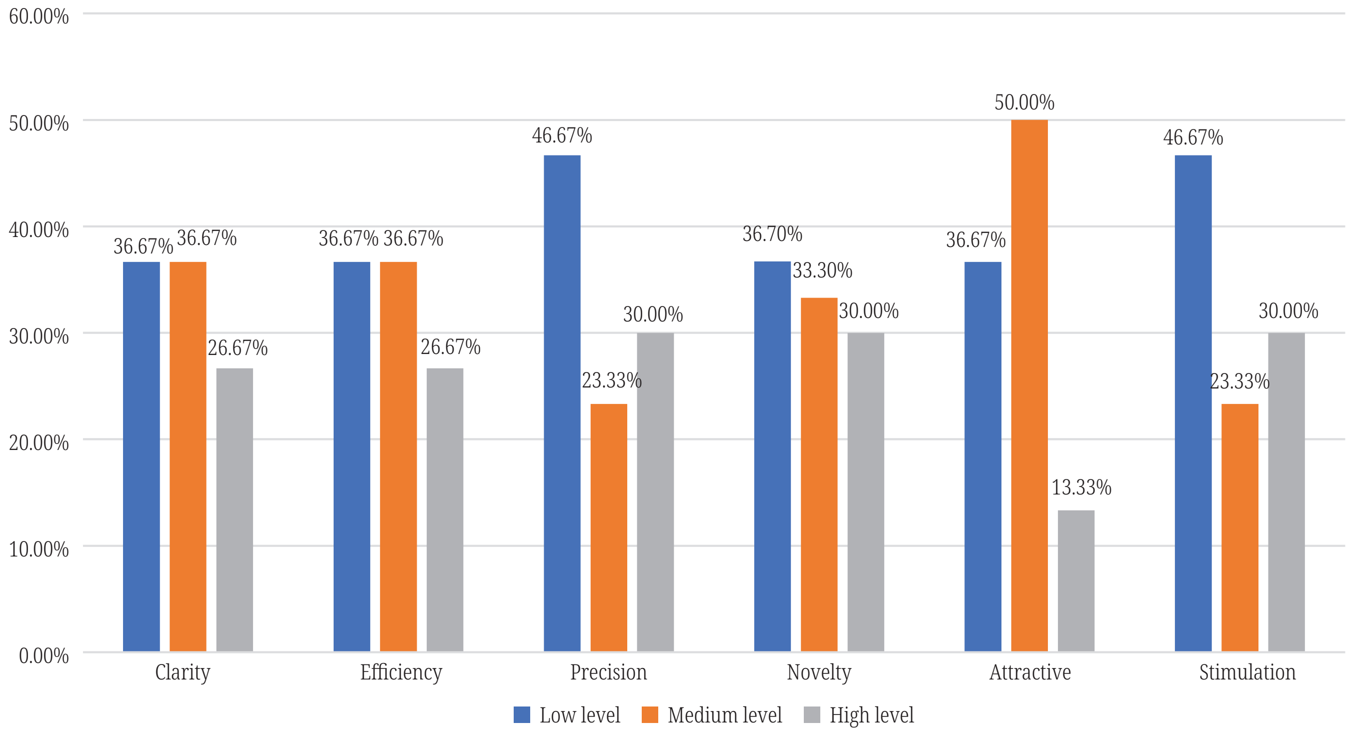

Fig. 7. Result of students' perception of the mobile application, obtained from the use of the UEQ instrument

From a usability perspective, the specific evaluation of the key dimensions—Clarity, Efficiency, and Accuracy—reinforces the conclusion that the application meets the fundamental principles of a good user experience. When analyzing the medium and high levels together, the overall perception of usability reaches 60%, as evidenced in Table 1, which shows that most students find the application functional and effective for their learning purpose.

Table 1. Results of the level of perception of usability, obtained from the use of the UEQ instrument

Level of Perception	Usability
Low level	40.00%
Medium level	32.22%
High-level	27.78%

The results obtained indicate that the TempRes ControlSys Simulator mobile application has been designed with an intuitive structure and efficient navigation, allowing a fluid interaction with the contents related to the temporal response of control systems and the tuning of PID controllers: These findings show that the mobile application offers a reliable and efficient environment for students, facilitating the understanding of key concepts in automatic control. Although there are always opportunities for improvement, the general perception of users reflects a moderate level in terms of usability. These results coincide with previous studies that have analyzed the impact of accessible interfaces and environments on the learning of control systems. In this regard, in the work developed by [32], they highlight the importance of having interactive simulation environments that allow students to experiment with dynamic systems in a flexible learning environment. Their study highlights how digital tools that incorporate practical simulations improve the understanding of complex concepts by reducing the dependence on physical laboratories and allowing students to explore different control scenarios in real time. In this sense, TempRes ControlSys Simulator contributes to this line of research by offering a platform that facilitates experimentation with PID controller tuning without requiring additional infrastructure. In the same sense, in the study carried out by [33], they underline the importance of integrated environments that facilitate remote access to virtual laboratories, which optimizes the usability and efficiency of educational applications in the field of automatic control.

From a broader perspective, the study addressed by [34] highlights the role of computational tools in engineering education, emphasizing the use of MATLAB and OCTAVE as key platforms for system simulation. In this context, TempRes ControlSys Simulator aligns with this trend by offering an accessible interface for tuning and auto-tuning PID controllers, allowing students to interact with control models without depending on specialized desktop software. Likewise, the possibility of running simulations from a mobile application reinforces the flexibility of learning, an aspect that has been identified as crucial in digital teaching environments. In the work developed by [35], it also shows the benefits of cloud platforms in the educational field, pointing out that their implementation facilitates accessibility without the need for complex installations. In this sense, TempRes ControlSys Simulator provides a friendly and easily accessible environment that optimizes the learning experience of engineering students, ensuring that they can concentrate on understanding concepts without facing technological barriers. Likewise, in the study conducted by [36], it is suggested that the integration of mobile tools in education requires not only intuitive interfaces but also content optimization processes that reduce the cognitive load of users. In this way, the TempRes ControlSys Simulator presents strengths in terms of clarity and ease of navigation, but future studies could explore improvements in the organization of content to further enhance the user experience and its usability in practical learning scenarios.

4.2 Load and Scalability Test Results

To evaluate the performance of the TempRes ControlSys Simulator mobile application, a load and scalability testing analysis was carried out using BlazeMeter. The initial load test configuration included a total of 50 virtual users (VUs), with a duration of 10 minutes and a load ramp-up time of two minutes. In addition, three ramp-up steps were established to distribute the load progressively and avoid peaks in the concurrent simulation. The request rate per second (RPS) was limited to 10 in order to analyze the behavior of the mobile application under progressive use conditions without saturating it prematurely. This configuration allowed us to obtain precise measurements on the server's responsiveness and the stability of the infrastructure hosted on Heroku, which imposed certain restrictions on the handling of high loads. Given the inherent limitations of the Heroku service and the purpose of ensuring efficient distribution of the mobile application to mechanical and electrical engineering students, the load test was run under these conditions, obtaining the values reflected in Table 2. It shows the results obtained for different load levels, starting with 10 virtual users and increasing to 50 simultaneous users. Metrics such as the average throughput (Hits/s), which reflects the number of requests processed per second, as well as the average response time (Avg. Response Time) and the 90th percentile of the response time (90% Response Time), which indicates the time in which 90% of the requests were answered, providing a more representative view of the performance under high demand conditions, were evaluated. It is observed that the throughput remains relatively stable around 3.05–3.22 Hits/s, which indicates consistency in the server's processing capacity. However, as the number of user increases, the average response time grows from 2.98 seconds with 10 users to 14.31 seconds with 50 users, showing a significant impact on latency.

Also, the 90th percentile of response time shows a progressive increase, reaching 28.33 seconds in the highest load scenario, suggesting that under high loads, a significant fraction of students experience long wait times. Finally, the error rate increases starting at 40 users, reaching 13.03 errors at the peak load level, indicating that the infrastructure at Heroku struggles to handle more than 30 concurrent users efficiently. These results underscore the need to optimize the backend infrastructure to improve scalability and ensure more competitive response times in high-demand environments.

Table 2. Mobile app load test results obtained from BlazeMeter

Max User (VU)	Samples	Avg. Throughput (Hits/s)	Errors	Avg. Response Time (Sec.)	90% Response Time (Sec.)	Avg. Bandwidth (KiB/s)
10	357	3.05	0.18%	2.98	5.43	140.13
20	681	3.12	0.29%	5.37	10.00	143.02
30	1171	3.07	0.34%	8.80	16.14	141.50
40	1885	3.15	1.49%	11.66	22.37	142.64
50	1927	3.22	13.03%	14.31	28.33	131.22

In order to further demonstrate the performance of the mobile application, tests were carried out with different levels of concurrent users, analyzing the behavior of the system under scenarios of 30, 40, and 50 simultaneous users. Figure 8 graphically shows the relative stability in terms of throughput and response times.

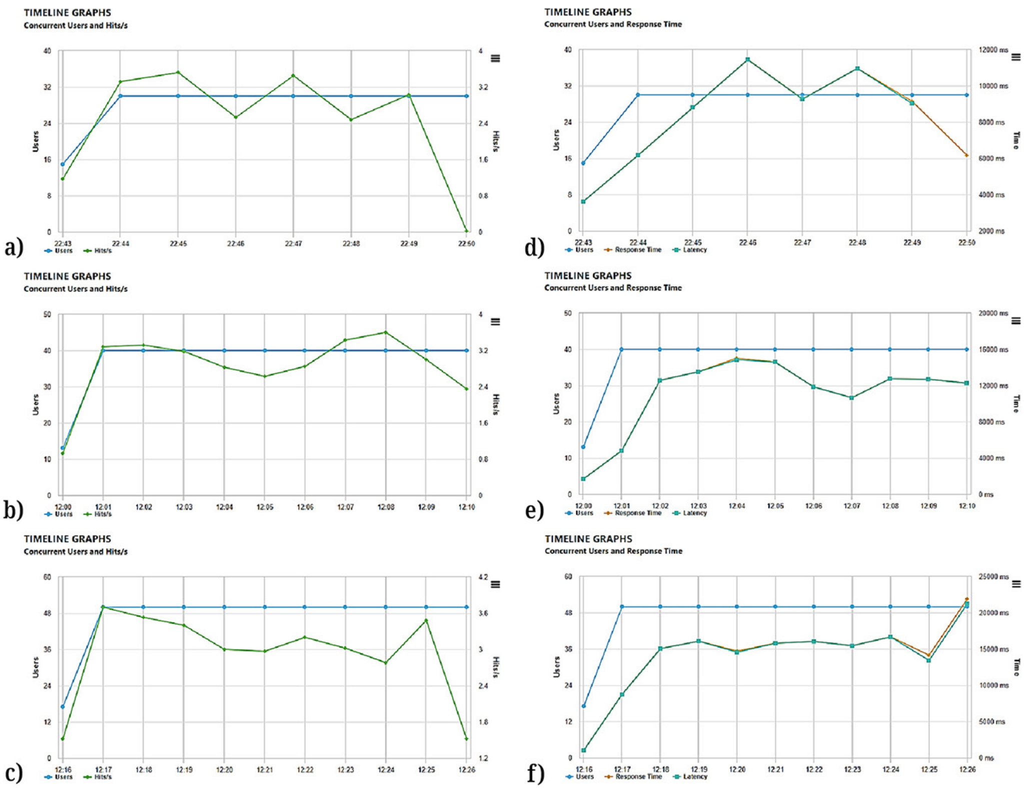

Fig. 8. (a) Relative stability in terms of throughput and response times for 30 concurrent users, (b) 40 concurrent users, (c) 50 concurrent users, (d) response time and 90th percentile for 30 concurrent users, (e) 40 concurrent users, (f) 50 concurrent users

In Figure 8a, corresponding to the execution of 30 users, it can be observed that the system maintains relative stability in terms of throughput and response times, without presenting a significant degradation in processing speed. This indicates that, in this load range, the infrastructure is still capable of handling requests efficiently without generating critical errors. However, in Figure 8b, with 40 concurrent users, an increase in response times and a slight variation in processing capacity begin to be evident, suggesting that the system begins to reach a limit in its operational capacity. While in Figure 8c, corresponding to the test with 50 users, a considerable increase in latency is observed, accompanied by an increase in the error rate. This behavior confirms that the infrastructure is having difficulty managing a high volume of simultaneous requests, affecting the user experience and the reliability of the service.

On the other hand, Figures 8d, 8e, and 8f reflect key performance metrics in each scenario, providing more detailed data on system degradation as the load increases. In Figure 8d, with 30 users, the response time remains within an acceptable range, with a controlled 90th percentile and a minimum error rate. In Figure 8e, with 40 users, a growth in response times is observed, and an increase in the number of errors, which, as already mentioned in the previous paragraph, for this number of users, the mobile application experiences a greater effort to process the requests. Finally, in Figure 8f, corresponding to the test with 50 users, a notable increase in latency and a significant increase in the error rate are evident, confirming that the system has reached a critical point in which the infrastructure is no longer able to efficiently handle the imposed load.

From the results obtained, it is evident that validating the performance of systems under high traffic conditions is relevant, since it allows ensuring an optimal user experience. In this sense, the evaluation of load and scalability under different levels of concurrent users has allowed identifying operational limits and anticipating possible bottlenecks in the mobile application, which is in line with the need to validate the system's performance in high-demand scenarios. Likewise, in accordance with the tool used to evaluate the performance of the mobile application, in the work carried out by [37], it is established that the implementation of Heroku as a cloud platform has allowed simulating realistic load scenarios and measuring key metrics such as throughput, latency, and error rate, in line with research that highlights the fundamental role of cloud computing in optimizing the performance of distributed applications. Furthermore, the study conducted by [38] emphasizes that the effectiveness of load testing depends largely on an accurate workload model, an aspect that has been addressed in this study by evaluating scenarios with 30, 40, and 50 concurrent users, which allowed analyzing the system's capacity to manage requests without compromising its reliability. In methodological terms, the choice of BlazeMeter as a testing tool is in line with research such as that conducted by [39], who highlights its use to simulate multiple users and generate detailed data on system behavior under stress conditions, which is essential for mobile applications intended for real-time learning. Likewise, the study conducted by [40] highlights the importance of using scalable platforms that allow dynamic adjustment of system resources based on demand, optimizing performance in digital educational environments and ensuring application stability under variable user loads. Finally, in this context, the work addressed by [41] establishes that to improve the scalability of applications in the cloud, it is essential to implement strategies such as optimization of database queries, efficient use of cache, and load balancing, which would allow the mobile application to achieve better performance in high concurrency scenarios without compromising the user experience.

5 CONCLUSION

From the results obtained, it can be concluded that the developed mobile application, named TempRes ControlSys Simulator, has proven to be a tool with an acceptable level of usability and performance, providing an accessible learning environment for Mechanical and Electrical Engineering students. Specifically, the usability evaluation based on the UEQ reflects a perception of 60%, which represents that students perceive a favorable perception in relevant dimensions such as clarity, efficiency, and precision, suggesting that the application facilitates the understanding of fundamental concepts such as the analysis of the temporal response of control systems and tuning and auto-tuning of PID controllers. Regarding the evaluation of the performance of the mobile application, the results show that the application maintains a stable performance up to 30 concurrent users, at which time acceptable response times and a low error rate are observed. Furthermore, since this case study considered a population of 30 students, and the mobile application achieved optimal performance up to 50 simultaneous users, it is confirmed that the infrastructure used was sufficient for the expected demand within the context of the study. In turn, the availability in the cloud through Heroku allows access to the application without the need for complex installations, eliminating technological barriers for students. Therefore, it is concluded that the development of the mobile application called TempRes ControlSys Simulator contributes to inclusion and sustainability in the teaching of control systems in low-resource contexts, where the acquisition of desktop simulation software with expensive licenses represents a barrier for students, mainly for those in developing countries. Thus, this mobile application becomes a viable alternative to democratize access to the simulation of PID controllers, allowing students to perform dynamic system analysis and tuning and auto-tuning tests without depending on specialized equipment.

6 FUTURE STUDIES

Given this scenario, it is recommended that future studies expand the current capabilities of the mobile application by integrating sensors that provide real-time information. Currently, the application uses user-defined transfer functions to simulate the behavior of automatic control systems; however, the incorporation of sensors such as the MPU9250 would allow obtaining real-time data directly from real experimental environments. This would facilitate a more direct interaction with physical systems and not just simulated ones, providing students with precise and contextualized information to improve the usability of the application and consequently the teaching-learning process. In this sense, the mobile application could function as a controller, receiving real signals from sensors such as accelerometers and gyroscopes, which could be used, for example, in the stability control of the propellers of a drone or in the precise manipulation of a robotic arm, relevant applications for Mechanical and Electrical Engineering students.

7 LIMITATIONS OF THE STUDY

This study has some limitations that need to be pointed out, considering their possible implications for the results obtained. First, the sample consisted of only 30 Mechanical and Electrical Engineering students, which could restrict the generalization of the results; future studies with larger and more diverse samples could offer more robust conclusions that can be extrapolated to other educational contexts. Second, the infrastructure contracted through the Heroku platform was limited to one Dyno, which restricted the maximum number of concurrent users who could participate in the load and scalability tests. This restriction could have led to an underestimation of the real potential of the mobile application under conditions of intensive use. Finally, although the usability evaluation was carried out using the UEQ instrument, its predominantly quantitative nature could have limited the capture of detailed qualitative information about the individual perceptions and experiences of the students, which would have enriched the interpretation and deeper understanding of the phenomenon studied.

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